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A REVIEW OF THE COLD ROLL BONDING OF ALSN ALLOY/STEEL BIMETAL STRIPS

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Abstract

The cold roll bonding (CRB) of aluminium alloys to steel is a key industrial manufacturing process tool used to generate bimetallic composites for engine components. By joining steel and aluminium alloys in the solid state the desired mechanical bearing properties of both metals can be achieved; thus allowing for superior tribological wear and strength characteristics observed in modern automotive bearings. CRB facilitates the joining of dissimilar metals at room temperature making it an economical and industry wide technique. The following work on CRB AlSn alloys to steel offers a critical literature review combined with internal research carried out in collaboration with MAHLE Engine Systems Ltd. MAHLE are a leading automotive bearing manufacturer who have established an effective continuous CRB production line; the only one of its type in the UK. The main process variables involved in CRB AlSn alloys to steel and in particular, what conditions are likely to facilitate the best possible bond strength are discussed. Surface preparation, the role of surface contaminants and oxides, reduction in thickness, friction coefficient, rolling speed and direction, annealing treatments, and suggested mechanisms for CRB are considered in relation to current production practice within MAHLE.

Keywords: Cold Roll Bonding, AlSn alloys, Steel

1. INTRODUCTION

Bimetal composites of Al alloy/steel possess hybrid properties deriving from the two dissimilar metals which makes them an ideal choice for both passenger car and truck vehicle bearings in the automotive manufacturing industry. Automotive bearings manufactured from cold bonded AlSn alloy/steel strip have overall improved anti-seizure properties, wear resistance and corrosion resistance, compared to earlier materials such as their babbitt bearing, predecessors [1].

The addition of tin to the aluminium alloy creates a complementary soft phase with further surface properties such as; embedability, conformability, and compatibility [2]. This is ideally suited to automotive bearings as they may be required to imbed small, foreign particles and conform to allow for any irregularity in shape whilst being compatible enough to resist welding under the heat and pressure within an engine. AlSn alloys are primarily bonded to steel by a cold roll bonding (CRB) or warm roll bonding (WRB) process [3]. Warm roll bonding is similar to CRB but, as the name suggests, the strip is roll bonded at an elevated temperature. Therefore, when utilising this method to bond Aluminium to steel, strict temperature control is required to ensure no brittle intermetallic compounds are formed. In CRB conversely, a solid state weld is established at room temperature by the joint plastic deformation of the metals to be bonded, thus making it a more practical and economical technique for industry [4, 5].

CRB is a topical area of interest for industry and review papers have already been published on the subject [6, 7]. However, to date papers have not focused on the CRB of AlSn alloys to steel despite this being the bimetal composite of choice for the majority of manufactured, domestic, automotive bearings. This work aims to further understand the factors that can affect the interface strength of cold roll bonded AlSn alloy/steel strip with MAHLE Engine Systems Ltd. providing access to CRB plant trials and industry based, internal research papers [8-11]. The studies reported outline the present understanding of cold roll bonded

AlSn alloys to steel from the available literature while identifying current research limitations and areas of future investigation.

2. THE COLD ROLL BONDING PROCESS

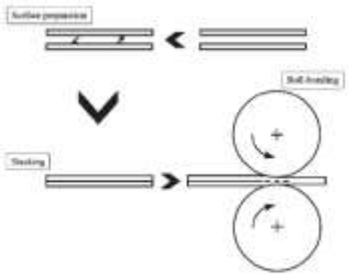


Fig.1 Schematic of CRB process [5]

CRB consists of stacking metal sheets or plates on top of each other and passing them through a pair of rolls in order to experience a substantial, simultaneous reduction which facilitates a solid state bond. MAHLE have a continuous roll bonding production line at their Kilmarnock, Scotland site which generates on average 40 Km of AlSn/Steel bimetal per week. Prior to CRB, the (clad) AlSn alloy and steel surfaces are subjected to mechanical and water based cleaning processes to achieve the requisite bond strength during the CRB process [12]. After rolling the bimetal is often subjected to a subsequent heat treatment to alleviate any strain caused by cold working the metals and to improve bond strength.

The main problem with creating a metallurgical bond between two dissimilar metals in a production environment is the difficulty of evaluating bond strength. Current industry practice uses destructive testing which is not ideal from a manufacturer's perspective. Destructive methods for evaluating bond quality include a chisel test [13], peel test [14-21], shear test [22, 23], Erichsen cup test [24], and the more outdated hot hammer test [9]. Each has it's own unique advantages and disadvantages. Accurate bond evaluation is more difficult when considering very thin composites like those made by MAHLE, where the AlSn alloy can be 0.5 mm thick. In cases like this the peel test has been proven to be the most accurate production evaluation method. Manesh [25] has recently proposed a new electrical resistivity test for Al/Steel where the difference between the theoretical and experimental resistivity is considered as the inherent resistivity of the bond, which would approach zero for ideal bonding. Work has also been performed to calculate and predict the interface properties using material mechanics theory [26].

3. MECHANISM OF COLD ROLL BONDING

Four theories have been proposed to explain the mechanism of CRB: the thin film [27-30], energy barrier [31-33], diffusion bonding [34] and joint recrystallization [35] theories. Mohamed and Washburn [32] and Vaidyanath and Milner [32] believe that the predominant one is the thin film theory, due to the low temperatures involved in CRB. The thin film theory states that when two adjacent brittle surfaces are brought together and subjected to pressure they will expand and break up coherently, leaving areas of underlying, nascent metal. Further roll bonding causes this nascent metal to extrude through the growing cracks in the surface layers and the highest asperities of the extruding metals meet to form cold welds. Bay [36] attempted to further simplify the thin film theory by distinguishing two bond formation mechanisms;

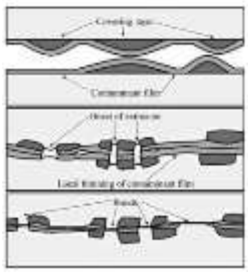


Fig. 2 Schematic of the thin film theory [7].

1. Where a work hardened surface layer is present such as that achieved by scratch brushing or linishing, the brittle cover layers of the surfaces will fracture as a result of surface expansion during rolling. Virgin metal then extrudes from interface surfaces and the highest asperities created form a metallic bond.

2. Where no brittle cover layer is present, bonding is achieved by the local thinning of the contaminant film which is normally composed of oxides, water and any other contaminants. This occurs when a threshold surface expansion is reached.

The threshold surface expansion R_t [30], is the minimum % reduction required for bonding to occur and can vary significantly depending on condition of the metal surface [37]. Figure 2 outlines the thin film theory mechanism for a scratch brushed surface where (a) shows two work hardened, brittle surfaces brought together, (b) shows the application of pressure results in surface expansion causing the brittle cover layers to crack and the contaminant film to thin and (c) shows the extrusion of virgin metal has resulted in the formation of cold welds, leaving isolated islands of the brittle cover layer. Optimum bonding occurs if the brittle cover layers break up coherently to produce areas of metallic bonding and small islands of brittle material.

In MAHLE's CRB production line, currently being studied, the surface of the steel is work hardened by a linishing process whereas the alloy surface is scratch brushed to produce the same effect. It was found that both linishing and scratch brushing generate the formation of a brittle cover layer required for optimum bonding under the thin film theory mechanism by introducing dislocations to the surface lattices.

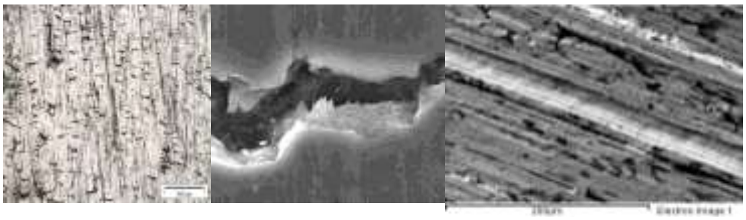


Fig. 3 SEM Micrographs

The images in figure 3, taken from MAHLE's internal research papers [38] show (a) a micrograph of the scratch brushed surface of aluminium after experiencing a surface expansion where cracking of the brittle cover layer is visible. (b) A high magnification SEM micrograph of a crack in the alloy surface, showing the fracture to be brittle. (c) A SEM micrograph of linished steel after experiencing a surface expansion where cracking of the brittle cover layer is visible. Cave [33] reported that when considering this mechanism an energy barrier must also be overcome in order for bonding to take place, as energy is required to disperse surface contaminants and rearrange surface atoms to achieve a boundary configuration. Parks [35] theorised that this energy barrier is, in fact, the energy required for recrystallization.

SEM analysis and images of the AlSn and steel surfaces after a peel test from plant studies are shown in figure 4. Areas of cold welding are evident and the bimetal appears to have experienced a ductile fracture.

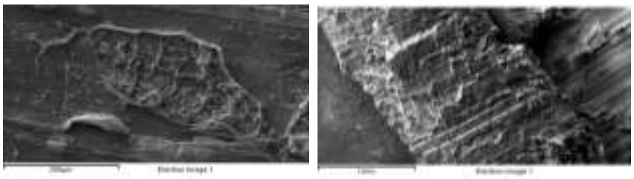


Fig. 4 SEM of (a) Steel and (b) AlSn surfaces after a peel test

It is understood that a mechanical bond is established initially by rolling and then a strong metallurgical bond develops. It is still not clear from the published literature and observations made in the plant environment if this metallurgical bond occurs during CRB or during the subsequent annealing treatment. Movahedi [15] has shown that diffusion does occur during the annealing of an Al/Steel bimetal, supporting the suggestion of metallurgical bond formation. Wu, Le and Wang [29] concluded in their research that mechanical bonding must precede diffusion and that diffusion itself is temperature and time dependent. Recrystallization is also likely to take place at the higher temperature of the heat treatment, again facilitating the development of a metallurgical bond. It is most likely that all 4 theories play a part in this complex bond development.

4. PARAMETERS AFFECTING BOND STRENGTH

4.1. Surface Preparation

It has been reported [24, 39] that degreasing surfaces followed by scratch brushing immediately before welding produces the strongest cold roll bonds due to the removal of contaminants and surface oxides which could interfere with the creation of nascent metal welds that can establish an effective cold weld. A good surface roughness is also generally considered to be beneficial, creating a larger amount of surface asperities and promoting localised sheer deformation to break unavoidable surface oxide films [40]. Parks [35] however suggested that a rough surface would produce low strength bonds as surfaces would only make contact over small areas (touching asperities). The authors believe this would only be the case with low rolling loads and little deformation. Durst [41] hypothesised that the main outcome of scratch brushing is the removal of adsorbed contaminant surface layers, as although oxides will be partially removed by scratch brushing it cannot produce an oxide free surface as scratch brushing heats the surface layers, most likely to their melting point [42], rapidly reforming an oxide layer. Agers and Singer [43] postulated that local deformation at the interface is more important than macroscopic deformation and that sheer displacement, along with increasing the contact area also destroys the continuity of any absorbed contaminants. Buchner et al. [44] achieved low bond strengths between Al/Steel sheets when using only degreasing as a surface preparation, and in contrast good bonding when surfaces were hardened by grinding and crucially the direction of grinding appeared to have no influence on the bond strength. It is generally accepted that there is an optimum surface preparation for the CRB of each combination of metals. Steel for example does not produce very high bond strengths from scratch brushing [45]. MAHLE has established that scratch brushing the aluminium and linishing the steel produces the strongest bonds. Plant trials are currently investigating the effect linishing belt grit size and brush type on the surface condition and how this affects bond integrity. Studies conducted by Tolaminejad and Arabi [46] and Bay and Zhang [47] showed that when using brittle surface coatings the surface hardness determined the amount of cold welds established. This is consistent with the thin film theory but here the cover layer of steel is comprised of a hard chromium interlayer (similar to anodising one surface). Bay [48] bonded aluminium strips that were either scratch brushed, Ni-plated or simply degreased in otherwise controlled conditions and shear tested. Scratch brushing produced the strongest sheer bond strength followed by Ni- plating.

4.2. Effect of Particles at Interface

The literature demonstrates that the presence of contaminant particles at the interface during CRB can result in bond failures. More recently the effects of specific particles have been investigated. Alizadeh and Padyar [49] studied the presence of TiH_2 particles on roll bonding Al/Al strips and found bond strength decreased. Jamaati and Toroghinejad [50] found that the presence of Al_2O_3 particles reduced the bond strength of CRB Al/Al strips. Current plant studies therefore seek process steps which will minimise aluminium oxide formation. Contrary to previous results, Lu et al. [51] used SiO_2 particles at the bond interface and found the bond strength of CRB aluminium sheets improved. The nano sized particles impede the movement of dislocations during sheer deformation and lead to a pile up of dislocations around the particles. This locally hardens the surface and enhances the bond strength. As the particles are harder than the material being bonded the particles fracture the oxide layers on the sheets being cold roll bonded, much like wire brushing but here there is no time for the oxide layer to reform.

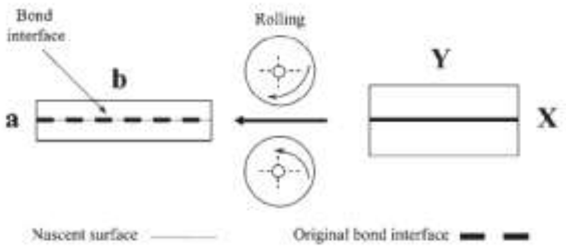
4.3. Oxide films

The best bond strengths are created by surfaces which are "baked out" (i.e. pre heated in an oven for a short period of time) prior to preparation as this removes any water vapour which if present at a potential bond interface for even a small amount of time can lead to reduced bond strengths [30]. This correlates with controlled plant trials which showed that deliberately contaminating the surface of the steel with water prior to CRB results in delamination. Tylcote [40] believed that bond strength decreases as the oxide thickness increases. However authors such as Donelean [42] have shown that aluminium surfaces with a thick anodised film on one surface give good bonds which are only 10% less than those achieved using scratch brushing. If both surfaces however exhibit thick anodised layers bond strength decreases, due to the increased thickness of the interface layers and the potential mismatch of cracks in the two anodised layers

[45]. In another study [30] it was reported that scratch brushed surfaces of aluminium sheets exposed to the atmosphere from 2 minutes to 10 days prior to CRB, that bond integrity decreased markedly after 15 minutes. Le et. Al [52] supported this conclusion where Al/Al bimetal strips were treated to give oxide film thicknesses from 24 nm to 15 μm prior to CRB. Cracks running perpendicular to the rolling direction were seen on the Al surfaces with the spacing between adjacent cracks increasing with oxide film thickness. Conversely, Barlow, Neilsen and Hansen [53] reported that aluminium strip coated in an oxide could be effectively CRB without surface preparation, where oxide dispersion was found to slightly enhance the thermal stability of the material. Tylecote, Howd and Furmidge [40] studied the importance of the ratio of hardness of the surface oxide film to that of the bulk metal in determining ability to bond. The oxide layer was left to form in situ after degreasing and scratch brushing metal surfaces. It was found for most metals the ratio of oxide film hardness to metal hardness was of little importance for bond intergrity. However it was again reported that increasing film thickness was detrimental to bond strength. These studies were completed when oxide hardness was stipulated in terms of Mohs's scale which even at the time was regarded as inaccurate. Modern nano hardness measurements could support future studies to extend an understanding of the importance of the ratio of oxide film to metal in relation to bond strength. On the basis of the hardness studies the authors believe a study of the hardness ratio of the scratch brushed and linished work hardened metal surfaces to their base metal could inform as to whether a relationship exists between bond strength and surface hardness. So far no such studies have been reported.

4.4. CRB Reduction factor

The Reduction in thickness (R_t) of a bimetal during cold roll bonding is the most influential of factors affecting bond strength [15, 54] as R_t is directly related to the extrusion of virgin metal by surface expansion [32]. A simplified schematic illustration of this is shown below in figure 5.



% reduction in thickness =X-a/X x 100% = (1-a/X) x 100%
% nascent (new) surface = b-Y/b x 100% = (1-Y/b) x 100%

Fig. 5 CRB schematic illustrating break up of brittle cover layer [18].

At a constant volume, assuming no change in width, i.e. XY =ab (or X/a=b/Y) the two equations are equivalent, where % reduction = % of nascent surface generated [18]

When CRB aluminium sheets Quadir et. Al [55] found that a reduction in thickness generated simple and branched sheer bands, perpendicular to the rolling direction, which helped to puncture the interfacial oxide layer and enhance bond toughness. Lee and Duggan [61] reported on observing the same phenomenon in the rolling of brass. The maximum strength of a CRB bimetal composite is when it becomes the same as the tensile strength of the weaker of the two bonding materials [56]. For this to happen at room temperature, welding deformations of up to 60-70% for Al/Al bimetals were reportedly required for weld strengths equivalent to the solid metal [32].

4.5. Initial Thickness

Previous research has shown that altering the initial thickness of incoming strip can change the location of the bond point within the roll gap and can change the bond strength [58]. Jamaati and Toroghinejad [18] increased the initial thickness of Al/Al bimetallic strips during CRB and observed a decrease in interlayer bond strength. Vaidyanath, Nicholas and Milner [30] also found that bond strength decreased with increasing initial thickness. However, the strength of the bimetal increased until the width/thickness ratio was a value of six, after which the strength remained constant. This is thought to be linked to the importance of pressure in CRB i.e. changing the thickness of incoming sheets may require more pressure to achieve the same amount of reduction.

4.6. Rolling Speed and Direction

Plant studies in the 1970's were conducted to establish a rate of bonding that would not affect the bond strength of the AlSn/St bimetal. At that time very little research had been carried out on how bonding speed related to out bond integrity. Two research papers [8, 9] document how various bonding speeds were trialled with the resulting bimetal evaluated by chisel test, hot hammer, hardness and metallographic examination. It was found that increasing the speed did eventually result in a poorer bond, leading to a limit being imposed on the speed of bonding at the production line that would not interfere with bond integrity. This research substantiates the reported literature which shows that rolling speed resulted in slightly lower bond strength at interfaces, due to a decrease in the contact time of the interfaces [5] and is seen to be more pronounced at higher reductions. Vaidyanath, Nicholas and Milner [30] concluded that bonding is promoted by low rolling speeds and large diameter rolls. Lowering the rolling speed is reported to decrease the threshold reduction, R_t [59]. Few studies have been conducted on the rolling direction's influence on bond strength. Jamaati and Toroghinejad [5] recently conducted a trial where strips were cut parallel to the transverse direction of the as rolled sheets, the surfaces were scratch brushed and then CRB. Tensile peel tests were conducted comparing them to strips rolled in the original direction. The average peel strength of samples rolled in the transverse direction were weaker than those rolled in the original direction. This is said to be due to the theory that bond strength partially depends on the total area of contact between the two surfaces. As the surface asperities of the strip will depend on the original roll surface asperities via a process of imprinting, then if this area of contact is larger in the original rolling than CRB it is thought to account for the decrease in bond strength [7]. This is difficult to understand as both the original and transverse surfaces were scratch brushed before bonding thus modifying and negating any imprint on the metal surfaces.

4.7. Friction Coefficient

Increased roll-strip friction in CRB is reported to give increased values of mean contact pressure, peel strength and therefore bond strength [18, 60]. Hosseini and Kokabi [61] studied the effect of three different lubricant conditions: no lubrication (μ = 0.15), poor lubrication (μ = 0.13) and normal lubrication (μ =0.11). The maximum peeling force was achieved with no lubrication i.e. a higher coefficient of friction. When lower friction coefficients and reductions were trialled, bonding was found to be unsuccessful. When the friction coefficient was increased R_t was seen to decrease. Manesh and Shahabi [24] similarly, also studied the effect of roll-strip friction on the bond strength of Al/Steel bimetal and trimetal strips and found that bond strength increased with increasing roll-strip friction coefficient.

4.8. Annealing

In the CRB process bimetal composites often undergo a heat treatment to modify the hardness created by the necessary reduction in thickness. This is known to improve the bond and can be carried out either pre or post rolling.

4.8.1 Pre-Rolling Annealing Treatment

Movahedi and Kokabi [15] investigated the roll-bonding of Al/Fe sheets at 50% reduction and reported a medium bond strength of 17.4MPa but results obtained from Nezahad and Ardakani [62] showed the bond strength of Al/Steel sheet with a 200°C preheat treatment and 45% reduction to approach that of aluminium.

Buchner [44] showed if the steel in an Al/Steel bimetal is pre-heat treated, the bond strength increases significantly due to the more similar flow characteristics of the metals. Conversely, if the Al is pre-heat treated, the bond strength diminishes and bonding results in only the mechanical interlocking between the surface asperities [39]. Jamaati and Toroghinejad [5] showed a pre-CRB annealing treatment caused the average peel strength of Al/Al strips to increase and the threshold deformation of bonding to decrease. Post rolling annealing treatment was also shown to improve bond strength in the aforementioned study but not to the same extent as a pre-rolling annealing treatment.

4.8.2 Post-Rolling Annealing Treatment

There is an optimum annealing time, temperature and reduction for every bimetal composite in terms of achieving good bond strength due to the amount of energy needed for recrystallisation (i.e. the time and temperature of annealing) which depends on the amount of deformation the bimetal composite has experienced. Yan and Lenard [3] found that the mechanical bonding mechanism is dominant in CRB, but in order to achieve bond strengths where the shear strength approached that of a parent metal, bonds that were created at room temperature were required to undergo a post rolling annealing treatment. In the aforementioned study by Movahedi and Kokabi [15] Taguchi methods were used to investigate bond strength and it was found that post annealing heat treatments give strong metallurgical bonds, improve joint strength [48] and reduce threshold reduction [55]. The annealing temperature however appeared to have the most effect on joint strength as the influence of annealing time was said to be entirely dependent on the annealing temperature. Enhancement of annealing temperature showed an increase in the bond strength until the formation of an intermetallic layer. Several studies have observed brittle intermetallic layers form at the bond interface [63] after heat treatment. The FeAl phase diagram [64] shows a high solubility for Fe in Al and three phases ζ (Al2Fe), η (Al5Fe2) and θ (Al13Fe4) exist. It has been proven that the addition of Si to Al can impede the growth of η in certain diffusion circumstances [65]. Few papers are in agreement as to the effect of this intermetallic layer on bond strength. Some say it's presence at the interface is detrimental to bond strength [66]. Others say very small amounts do not have any adverse effect on bond strength [15]. The exact amount of acceptable intermetallic layer is not agreed by researchers, and while it has been suggested that the critical intermetallic layer thickness is 2.6μm [60], others claim 3-5μm is okay but at 10μm the bond is compromised [63], while others suggest 4-5μm thickness as a limiting thickness to avoid delamination [66]. The thickness of intermetallic phase on the surfaces of Al/Steel increased with increasing annealing temperature up to 500ºC at a constant annealing time [54]. Conversely Li et al. [67] showed that there was no change at the joint interface of Al-1050/STS-304 roll bonded sheets up to 400˚C. Buchner [44] proved that after post heat treatment the highest bond shear strength is reached, independent of initial bond properties, due to the hardening process of reductions. Tylecote and Wynne [40] reported CRB of Al/Al using up to 60% reduction where the bond improved with heat treatment. However the treatment appeared to have no detectable effect on the micro-structure or mechanical properties. This improvement is therefore thought to be due to local atomic rearrangement at the bond interface. Plant trials have been conducted using a small oven to replicate large bimetal coil annealing cycles. The objective is to increase the annealing temperature and improve bond strength until the formation of an intermetallic layer, where the effect on bond is then determined by a tensile peel test. This study will contribute to the current debate on the subject.

5. DISCUSSION

All the aforementioned theories for why a certain surface preparation facilitates a strong bond fit with the thin film theory mechanism for bonding. They all involve removing surface layers, cracking them or reducing contamination to result in a larger area fraction of nascent metal welds at the interface, thus increasing bond strength. It is the work utilising different surface preparation techniques that helps to explain the mechanism further. Tolaminejad [46], Bay [47] and Zhang [45], when investigating the suitability of hard coatings as a form of surface preparation, found brittle coatings which fractured resulted in good bond strengths; this supports the theory that surface hardness is key to the bonding mechanism. This has been further supported by internal plant trials that show mechanically prepared, work hardened surfaces also crack in the same manner. Conflicting results were reported for oxide films however, some studies showing increased bond strength and others showing diminished bond strength which may be explained by the variation in the nature of the surface oxides. A hard anodised oxide on the surface gives cracking and exposure of nascent material whereas oxide layers created from atmospheric water vapour reduce the amount of exposed nascent material, resulting in poor bond strengths [40]. SiO_2 nano particles are reported to increase bond strength by hardening the surface and instantaneously removing oxide layers but unfortunately to date it has not been found suitable for industrial application. However Padyar [49] did not have a similar success with TiH_2 nano particles which could have been expected to give a similar result. R_t is clearly crucial to what occurs at the bond interface and all authors agree on this. The little work reported on rolling direction suggests it has an effect on the bond. Literature findings and internal reports indicate that bond strength decreases with increased rolling speed. Pre rolling annealing treatments are reported to increase subsequent bond strength more than post annealing treatments and crucially this appears to be beneficial for the steel, but detrimental to the alloy. All authors agree that post rolling annealing treatments improve bond strength, and most stipulate that temperature has a greater effect than time, however Fe_xAl_x compounds at the interface are still a topic of debate with no agreement on how much of this intermetallic can be tolerated.

6. CONCLUSION

It can be concluded that a full understanding of the thin film mechanism is key to optimising CRB production processes and more investigative work is needed. Surface preparation and nascent surface generation are fundamental to ensuring a strong bimetal bond. Post rolling annealing treatments improve joint strength along with annealing the steel pre-CRB. Rolling speed and the roll-strip friction coefficient are also capable of effecting weld strength. Much of the research into CRB took place in the 1950-1980's and there is now a need for further studies to consolidate current theories and explain earlier conflicting results.

ACKNOWLEDGEMENTS

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